Volumetric *k*-means clustering for 3D SEISMIC FACIES ANALYSIS – PROGRAM kmeans3d

Overview



K-means (MacQueen, 1967) is perhaps the simplest clustering algorithm and is widely available in commercial interpretation software packages. **kmeans3d** is a volumetric seismic classification application that takes multiple seismic attributes as input, and generates a facies volume using *k*-means clustering. In **kmeans3d**, a user needs to specify the number of facies (clusters) to be generated, which is the *k* value in the *k*-means algorithm. Because the size of seismic data, in this implementation the software only takes a subset of data, extracted using a user specified decimation rate, to build a classifier, then apply this classifier to the whole 3D volume.

K-means is fast and easy to implement. Unfortunately, the clustering has no structure such that there is no relationship between the cluster numbering and the proximity of one cluster to another. This lack of organization can result in similar facies appearing in totally different colors, confusing the interpretation. Therefore, special care are needed when interpreting facies maps generated by *k*-means.

Theory

The workflow of computing *k*-means in **kmeans3d** is described here:

- 1. Decimate the input seismic attributes and store data in attribute space, i.e. each dimension is a seismic attribute.
- 2. Compute the eigenvalues, eigenvectors, and covariance matrix of input data in the attribute space, and use these to normalize data (same as z-score, which is for each data vector, measuring how many standard deviations away from the mean).
- 3. Initialize k centroids (mean of each cluster) uniformly in the normalized attribute space.
- 4. Perform *k*-means iteratively until change in centroids is smaller than a threshold value, or the algorithm reaches a user defined maximum number of iteration. The *k*-means updating process is shown in the figure below.
- 5. Apply the classifier to the whole dataset, assign each data vector to the cluster of the nearest centroid.



Cartoon illustration of a k-means classification of three clusters in a 2D attribute space. (a) Select three random or equally spaced, but distinct, seed points, which serve as the initial estimate of the vector means of each cluster. Next, compute the Mahalanobis distance (defined below) between each data vector and each cluster mean. Then, color code or otherwise label each data vector to belong to the cluster that has the smallest Mahalanobis distance. (b) Recompute the means of each cluster from the previously defined data vectors. (c) Recalculate the Mahalanobis distance from each vector to the new cluster means. Assign each vector to the cluster that has the smallest distance. (d) The process continues until the changes in means converge to their final locations. If we now add a new (yellow) point, we use a Bayesian classifier to determine into which cluster it falls (figure courtesy S. Pickford).

The Mahalanobis distance, r_{jq} , of the j^{th} sample from the q^{th} cluster center, θ_q , is defined as

$$r_{jq}^{2} = \sum_{n=1}^{N} \sum_{m=1}^{N} (a_{jn} - \theta_{nq}) C_{nm}^{-1} (a_{jm} - \theta_{mq}),$$

where the inversion of the covariance matrix, \mathbf{C} , takes place prior to extracting the mn^{th} element.

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This Program **kmeans3d** is launched from the *Volumetric Classification* in the main **aaspi_util** GUI.

Computing kmeans3d module

Setting the primary parameters is the first step of analysis. Use the browser on the first eight lines to choose the input seismic data file (*Arrow 1*). It is not mandatory to take in eight inputs. The number of inputs can vary from two – eight. The input attributes that one considers for facies analysis will vary according to the specific applications. For identifying the depositional facies variation the volumetric attributes such as dip magnitude, coherency, GLCM attributes, spectral magnitude, coherent energy can be considered as input. For characterizing geo-mechanical variation in shale plays one should consider different volumes that helps in identifying the rock physics such as inversion volumes, lambda-rho, mu-rho, intercept or gradient AVO volumes, etc. Specify the number of input attributes in the field labeled "Number of attributes to use" (*Arrow 2*). This value will be updated automatically when a file is selected. Do not forget to give a "Unique Project Name". A z-score algorithm is used to normalize the input files. The number of desired cluster is the *k* value in the *k*-means algorithm (*Arrow 3*). Empirically, we want a *k* value relatively small. Put the maximum *number of data training iterations* (*Arrow 4*). Select the decimation rate of input data used for training (*Arrow 5*).

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Then a user need to define the operation window in the **Operation Window** tab shown below.



Horizon definition

The horizon definition panel will look the same for almost all AASPI GUIs:

- 1. Start time (upper boundary) of the analysis window.
- **2.** End time (lower boundary of the analysis window.
- **3.** Toggle that allows one to do the analysis between the top and bottom time slices described in 1 and 2 above, or alternatively between two imported horizons. If *USE HORIZON* is selected, all horizon related options will be enabled. If the horizons extend beyond the window limits defined in 1 and 2, the analysis window will be clipped.
- 4. Browse button to select the name of the upper (shallower) horizon.
- 5. Button that displays the horizon contents (see Figure 1).
- 6. Button to convert horizons from Windows to Linux format. If the files are generated from Windows based software (e.g. Petrel), they will have the annoying carriage return (^M) at the end of each line (Shown in Figure 1). Use these two buttons to delete those carriage returns. Note: This function depends on your Linux environment. If you do not have the program **dos2unix** it may not work. In these situations, the files may have been automatically converted to Linux and thus be properly read in.
- 7. Browse button to select the name of the lower (deeper) horizon.
- 8. Button that displays the horizon contents (see Figure 1).
- 9. Button to convert horizons from Windows to Linux format. (see 6 above).
- **10.** Toggle that selects the horizon format. Currently *gridded* (e.g. EarthVision in Petrel) and *interpolated* (ASCII free format, e.g. SeisX) formats are supported. The gridded horizon are nodes of B-splines used in mapping and have no direct correlation to the seismic data survey. For example, gridded horizons may be computed simply from well tops. The x and y locations are aligned along north and east axes. In contrast interpolated horizons have are defined by *line_no*, *cdp_no* (*crossline_no*) and *time* triplets for each trace location. Examples of both format are shown in Figure 1. If *interpolated* is selected, the user needs to manually define each column in the file.
- **11.** Number of header lines to skip in the *interpolated* horizon files.
- 12. Total number of columns in the *interpolated* horizon files.
- **13.** Enter the column number containing the *line_no (inline_no)* of the interpolated data triplet.
- **14.** Enter the column number containing the *cdp_no* (*crossline_no*) of the interpolated data triplet.
- **15.** Enter the column number containing the *time* or *depth* value of the interpolated data triplet.
- 16. Znull value (indicate missing picks) in the horizon files.
- **17.** Toggle to choose between positive down and negative down for the horizon files (e.g. Petrel uses negative down).
- 18. Choose the vertical units used to define the horizon files (either s, ms, kft, ft, km, or m).

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| 144550 00000 439725 00000 1351,73165 501 5 ^{-M} 1485450 00000 439737 50000 1351,73128 501 6 ^{-M} 1485450 00000 439737 50000 1351,73128 501 6 ^{-M} 1485450 00000 439737 50000 1351,73128 501 6 ^{-M} 1485450 00000 439375 00000 1351,31342 459 7 ^{-M} 1485450 00000 439375 00000 1351,31342 459 7 ^{-M} 1485450 00000 439375 00000 1351,31342 459 7 ^{-M} 1485450 00000 439375 00000 1351,31342 500 7 ^{-M} 1485525 00000 1351,31426 500 7 ^{-M} 1485450 00000 439376 250000 1351,31405 500 7 ^{-M} 1485450 00000 439376 250000 1351,310554 508 8 ^{-M} 133 204630 510781 1239 4362 ^{-M} 133 204630 510781 1239 432 ^{-M} 1485457 00000 4393775 00000 1351,310524 508 8 ^{-M} 133 204450 510781 1239 432 ^{-M} 1485457 00000 4393775 00000 1351,310524 508 8 ^{-M} 1485457 00000 4393775 00000 1351,310524 508 8 ^{-M} 133 204450 510781 1239 432 ^{-M} 1485457 00000 4393775 00000 1351,31054 486 9 ^{-M} 1485452 00000 4393775 00000 1351,31054 486 9 ^{-M} 1485452 00000 4393775 00000 1351,31054 486 9 ^{-M} 1485450 000000 4393775 000000 1351,31054 486 9 ^{-M} 1485450 000000 4393775 00000 1 | 1485475.000000 4939725.000000 1852.000244 500 5^M | | 1 23 2045830 510781 1237.7449^M | |
| 1485450 000000 459737 500000 1551,71236 500 6 °M 1485457 500000 459737 500000 1551,71236 500 6 °M 1485457 500000 459737 500000 1551,71236 459 7 °M 1485550 000000 459737 500000 1551,71236 459 7 °M 1485550 000000 459737 500000 1551,71236 459 7 °M 1485550 000000 459775 00000 1551,11237 501 6 °M 1485550 00000 459775 00000 1551,11237 501 6 °M 1485550 00000 459775 00000 1551,11237 501 7 °M 148550 000000 459775 00000 1551,11266 501 7 °M 148550 000000 459775 00000 1551,510254 498 9 °M 148550 000000 459775 00000 1551,11276 498 9 °M 148540 00000 459775 00000 1551,11276 498 9 °M 148540 00000 459775 00000 1551,11266 498 9 °M 148540 00000 459775 00000 1551,1126 498 9 °M | 1485500.000000 4939725.000000 1851.571655 501 5^M | | 1 24 2045940 510781 1237.2827"M | |
| 1484570 000000 439737 500000 1851,71729 500 6°M 148550 000000 439737 500000 1851,71729 500 6°M 148550 00000 43977 500000 1851,71729 500 6°M 148552 00000 43977 500000 1851,71729 148552 00000 43977 500000 1851,71729 148552 00000 43977 500000 1851,71729 148552 00000 43977 500000 1851,71729 148552 00000 43977 500000 1851,71264 502 7°M 148552 00000 43977 500000 1851,71264 502 7°M 148552 00000 43977 500000 1851,71264 509 8°M 148552 00000 43977 500000 1851,71264 500 8°M 148552 00000 43977 50000 1851,51055 498 8°M | 1485450.000000 4939737.500000 1851.743408 499 6 ^M | | 1 26 2046160 510781 1237 4924 M | |
| 148250000000403972,5000001351,341395,341395,34039,74 14835500000004393750,000001351,3134355,5007,7M 14835500000004393750,000001351,3134355,5007,7M 14835500000004393750,000001351,3134355,5007,7M 14835500000004393750,000001351,3134355,5007,7M 14835500000004393750,000001351,313435,5007,7M 14835500000004393750,000001351,314345,5007,7M 14835500000004393750,000001351,314345,5007,7M 14835500000004393750,000001351,314345,5007,7M 14835500000004393750,000001351,314363,578,7M 1483550000000439376,5000001351,31435,500,87,87M 14835500000000439376,5000001351,31435,500,87,87M 148355000000004393775,000001351,314325,500,87M 148355200000004393775,500001351,314235,500,87M 148355200000004393775,5000001351,314235,500,87M 14855200000004393775,500001351,314235,500,87M 14855200000004393775,500001351,314235,500,87M 14855200000004393775,500001351,314235,500,87M 14855200000004393775,500001351,314235,500,87M 14855200000004393775,5000001351,314235,489,87M 14855200000004393775,5000001351,314235,489,87M 14855200000004393775,0000001351,510254498,97M 14854200000004393775,0000001351,510254498,97M 14854200000004393775,0000001351,510254498,97M 1485425,00000004393775,0000001351,510254498,97M | 1485475.000000 4939737.500000 1851.771729 500 6 ^M | | 1 27 2046270 510781 1237.4955^M | |
| 1485450 000000 4939750 000000 1351 1372784 496 9 7 M 1485457 000000 4939750 000000 1351 1372784 496 7 7 M 1485457 000000 4939750 000000 1351 13125 500 7 M 1485550 000000 4939750 000000 1351 13126 501 7 M 1485550 000000 4939750 000000 1351 13126 501 7 M 1485550 000000 4939760 00000 1351 14166 5102 7 M 1485550 000000 4939762 50000 1351 14166 5407 8 M 1485550 000000 4939762 50000 1351 14166 5497 8 M 1485550 000000 4939762 50000 1351 1405273 498 8 M 1485450 000000 4939762 50000 1351 1405275 498 8 M 1485450 000000 4939762 50000 1351 1405275 498 8 M 1485450 000000 4939762 50000 1351 1405275 498 8 M 1485455 000000 4939775 00000 1351 130254 501 8 M 1485550 00000 4939775 00000 1351 130254 501 8 M 1485550 00000 4939775 00000 1351 130254 501 8 M 1485550 00000 4939775 00000 1351 130254 496 9 M 1485550 00000 4939775 00000 1351 10234 497 9 M 1485450 00000 4939775 00000 1351 10234 498 9 M 1485450 00000 4939775 00000 1351 10234 497 9 M 1485450 00000 4939775 00000 1351 10234 498 9 M 1485450 00000 4939775 00000 1351 10234 497 9 M 1485450 00000 4939775 00000 1351 10234 497 9 M 1485450 00000 4939775 00000 1351 10234 497 9 M 1485450 00000 4939775 00000 1351 11234 497 9 M 1485450 00000 4939775 00000 13 | 1485500.000000 4939757.500000 1851.674194 501 6°M | | 1 28 2046380 510781 1237.8868^M | |
| 1485475 000000 459750 000000 1851 813452 500 7°M 148550 000000 459750 000000 1851 81505 501 7°M 148550 000000 459750 00000 1851 81505 501 7°M 148550 000000 459750 00000 1851 81465 4502 7°M 148560 000000 459775 00000 1851 81466 4578 °M 1485525 000000 459775 00000 1851 81466 500 7°M 1485525 00000 459775 00000 1851 126255 468 6°M 1485525 00000 459775 00000 1851 1270 2500 8°M 1485525 00000 459775 00000 1851 510555 408 8°M 1485525 00000 459775 00000 1851 510555 408 8°M 1485525 00000 459775 00000 1851 510555 408 8°M 1485525 00000 459775 00000 1851 510554 496 9°M 1485425 00000 459775 00000 1851 510554 498 9°M 1485425 00000 459775 000000 1851 510554 498 9°M | 1485450.000000 4939750.000000 1851.378784 499 7^M | | 1 29 2046490 510781 1238.4445^M | |
| 148550 000000 439750 00000 1352 0164 502 7*M 148550 00000 439750 00000 1352 0164 502 7*M 1485450 00000 439762 50000 1352 0164 502 7*M 1485450 00000 439762 50000 1352 0165 508 8*M 1485455 00000 439762 50000 1351 23625 508 8*M 1485552 00000 1353 26625 508 8*M 1485552 00000 1353 26625 508 8*M 1485552 00000 1353 26625 508 8*M 1485552 00000 1353 2675 501 8*M 1485552 00000 1353 2675 501 8*M 1485552 00000 1353 13602 62 8*M 1485552 00000 1351 1238 276*M 1485550 00000 439775 00000 1351 1058 459 9*M 1485550 00000 1351 1158 1497 9*M 1485550 0000 1351 1158 1158 1497 9*M 1485550 0000 1351 1158 1497 9*M 148550 00000 1351 1158 1497 9*M 148550 00000 1351 1158 1497 9*M 148550 00000 1351 1158 1158 1497 9*M 148550 00000 1351 1158 1158 1158 1158 1158 1158 1158 | 1485475.000000 4939750.000000 1851.413452 500 7^M | | 1 30 2046500 510781 1239.0701 ^{-M} | |
| 1485525 000000 459775 000000 1851 41065 477 °M 1485400 00000 459762 50000 1851 41065 477 °B M 1485400 00000 459776 50000 1851 1236 255 468 °B M 1485425 00000 459776 50000 1851 1236 255 468 °B M 14854575 00000 459775 50000 1851 519725 501 °B M 1485555 00000 459775 50000 1851 519725 501 °B M 1485552 00000 459775 50000 1851 510254 496 °F M 1485425 00000 459775 00000 1851 510254 496 °F M 1485425 00000 459775 00000 1851 510254 496 °F M 1485425 00000 459775 00000 1851 510254 496 °F M 1485425 00000 4599775 00000 1851 510254 496 °F M 1485425 000000 4599775 00000 1851 510254 496 °F M 1485425 000000 4599775 00000 1851 510254 496 °F M 1485425 000000 4599775 00000 1851 510254 498 °F M 1485425 000000 459775 000000 1851 510254 498 °F M 1485425 000000 459775 00000 1851 510254 498 °F M 1485425 000000 459775 000000 1851 510254 498 | 1485500.000000 4939750.000000 1851.851196 501 7^M | | 1 31 2046/20 510/81 1239.0334 M | |
| 1485425 000000 439376 20000 1351 2365 500 8°M 1485425 00000 439376 20000 1351 2365 500 8°M 1485455 00000 439376 20000 1351 2365 500 8°M 1485457 00000 439376 20000 1351 2365 500 8°M 1485457 00000 439376 20000 1351 2375 501 8°M 1485575 00000 1359 7156 456 9°M 1385225 0000 1359 7156 456 9°M 1485457 00000 1359 7156 456 9°M 1485457 00000 1359 7156 456 9°M 1485457 00000 1359 7156 456 9°M 1485458 00000 1359 7156 456 9°M | 1485525.000000 4939750.000000 1852.091064 502 7^M | | 1 33 2046930 510781 1239.9292^M | |
| 14034550 000000 439775 50000 1851 50025 500 6 M 14034575 000000 439762 50000 1851 57025 500 6 M 1403575 000000 439762 50000 1851 57025 500 8 M 1403555 000000 439775 00000 1851 57025 500 8 M 1403555 00000 439775 00000 1851 510254 496 9 M 1403525 00000 439775 00000 1851 510254 496 9 M 1403425 000000 439775 00000 1851 510254 496 9 M 1403425 000000 439775 00000 1851 510254 496 9 M 1403425 000000 439775 00000 1851 510254 496 9 M 1403425 00000 439775 00000 1851 510254 496 9 M 1403425 00000 439775 00000 1851 510254 496 9 M 1403425 00000 439775 00000 1851 510254 496 9 M 140342 000000 439775 00000 1851 510254 496 9 M 140342 000000 439775 000000 1851 510254 496 9 M 140342 000000 439775 00000 1851 510254 496 9 M 140342 000000 439775 000000 1851 510254 496 9 M 140342 000000 439775 000000 1851 510254 496 9 M 140342 000000 439775 00000 1851 510254 496 9 M 140342 000000 439775 00000 1851 | 1485400.000000 4959762.500000 1851.414063 497 8 °M | | 1 34 2047040 510781 1239.6946^M | |
| 1485475 000000 439775 00000 1851 1376025 5018 °M 1485500 000000 439762 50000 1851 376025 5018 °M 1485520 000000 439762 50000 1853 580200 5028 °M 14853753 000000 1350 71264 6496 °M 1485425 000000 1350 71264 6496 °M 1485425 000000 1350 71264 6496 °M 1485425 000000 1351 137612 4898 °M 1485425 00000 1351 137612 4898 °M 1485425 00000 1351 137612 4898 °M | 1485425.000000 4939762 500000 1851 405273 499 8 M | | 1 35 2047150 510781 1239.4829^M | |
| 1485500 000000 459762:50000 1851.59026 501 8° M 1 38: 2047400 510781 1238:2074° M 1485525 000000 459775: 000000 1853.59026 8° M 1 39: 2047800 510781 1239:0051° M 1485525 000000 459775: 000000 1853.59026 8° M 1 39: 2047800 510781 1239:0051° M 1485400 000000 4599775: 000000 1853.510254 496 9° M 1 40: 2047800 510781 1239:0051° M 1485402: 000000 4599775: 000000 1853.510254 496 9° M 1 42: 2047802 510781 1238:276° M 1485402: 000000 4599775: 000000 1853.510254 496 9° M 1 42: 2047802 510781 1238:2734° M 1485402: 000000 4599775: 000000 1853.510254 496 9° M 1 42: 2047802 510781 1238:2734° M 1485402: 000000 4599775: 000000 1853.510254 496 9° M 1 42: 2047802 510781 1238:2734° M | 1485475.000000 4939762.500000 1851.379028 500 8^M | | 1 36 2047260 510781 1239.3917 ^{-M} | |
| 1485525 000000 459775 00000 1853 580200 502 8°M 14854375 000000 1580,71264 659 9°M 14854525 000000 1580,71264 659 9°M 14854525 000000 1585,71264 659 9°M 14854525 00000 1585,71264 659 9°M 14854525 00000 1585,71264 459 9°M 1485425 00000 1585,71264 459 9°M 1485425 00000 1585,71264 459 9°M 1485425 00000 1585,71264 459 9°M | 1485500.000000 4939762.500000 1851.937256 501 8 M | | 1 38 2047480 510781 1239.2074^M | |
| 1483575 000000 4939775 000000 1851, 150854 496 9 M 1 40 2047700 510781 1238 6276 M 1485402 000000 4939775 000000 1851, 150854 497 9 M 1 40 2047700 510781 1238 7744 M 1485402 000000 4939775 000000 1851, 150854 498 9 M 1 42 2047802 510781 1238 7734 M 1485402 00000 4939775 00000 1851, 150854 498 9 M 1 42 2047802 510781 1238 7734 M 1485402 00000 4939775 00000 1851, 150854 498 9 M 1 42 2047802 510781 1238 7734 M 1485402 00000 4939775 00000 1851, 150854 498 9 M 1 42 2047802 510781 1238 7734 M 1485402 00000 4939775 00000 1851, 150854 498 9 M 1 42 2047802 510781 1238 7734 M 1485402 00000 4939775 00000 1851, 150854 1238 7734 M 1 42 2047802 510781 1238 7734 M | 1485525.000000 4939762.500000 1853.580200 502 8^M | | 1 39 2047590 510781 1239.0051^M | |
| 1485425.0000000 1959775.000000 1555.10564.499 9 M 1485425.00000 10555.10574.498 9 M 1485425.00000 1555.10574.1288.7734 M 1484252.00000 1555.10574.1288.7734 M 1 4 2047820 510781 1288.7734 M 1 4 2047820 510781 1288.7734 M | 1485375.000000 4939775.000000 1850.712646 496 9^M | | 1 40 2047700 510781 1238.8276^M | |
| 128624Ch hhnnnn 2636375 hhnnnn 1851 636371 266 6-M I Close | 1485400.000000 4939775.000000 1851.130981 497 9 M | | 1 41 2047810 510781 1238.7441^M | |
| Glose | 1485450 000000 4939775 000000 1851 639771 499 9 M | - | 1 42 204/920 510/81 1238.//34°M | - |
| <u></u> | | Class 1 | | |
| | _ | Zioze | | |

Figure 1. (left) A gridded horizon file (EarthVision format). (right) An interpolated horizon file with five columns (ASCII free format).

After defining the parallelization parameters, press the *Execute kmeans3d*.

| Primary parameters Operation Window Parallelization parameters | | | | | | | |
|--|------------------|--|--|--|--|--|--|
| Use MPI: 🗹 | | | | | | | |
| Processors per node: 8 Determine Maximum Processors on localhost | | | | | | | |
| Node list (separated by blanks): localhost | | | | | | | |
| Build an LSF Script? Do Not Run Under LSF | | | | | | | |
| Build a PBS Script? Do Not Run Under PBS | | | | | | | |
| Maximum LSF run time (hrs): 10 | | | | | | | |
| Available batch processors: 0 | | | | | | | |
| Determine Optimum Number of Batch Processors | | | | | | | |
| LSF Batch Queue: | | | | | | | |
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| | | | | | | | |
| (c) 2008-2015 AASPI - The University of Oklahoma | Execute kmeans3d | | | | | | |

The generated facies file is named as: kmeans_cluster_number_\${unique project name}_\${suffix}.H

Visualization of the result

To view the resulted facies map, a user can either use aaspi_plot, or import the facies volume into another commercial seismic interpretation software. If using a commercial interpretation software, remember to use a discrete colorbar, or turn off the value interpolation, because the values in a *k*-means generated facies map are discrete values. The figure below is a facies map from *k*-means along a horizon in a turbidite system in Canterbury basin, New Zealand. We interpret the white arrows as multistoried channels, black arrows as sinuous channel complexes, blue arrows as a sand filled channel, and red arrows as slope fans.



References

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- Zhao, T., V. Jayaram, A. Roy, and K. J. Marfurt, 2015, A comparison of classification techniques for seismic facies recognition: Interpretation, **3**, SAE29-SAE58.